Journal of Science Education and Technology, Vol. 15, No. 5, December 2006 (© 2006)
DOI: 10.1007/s10956-006-9022-6

Visualizing Without Vision at the Microscale: Students With Visual Impairments Explore Cells With Touch

M. Gail Jones,[1,4] James Minogue,[2] Tom Oppewal,[1] Michelle P. Cook,[3] and Bethany Broadwell[1]

Science instruction is typically highly dependent on visual representations of scientific concepts that are communicated through textbooks, teacher presentations, and computer-based multimedia materials. Little is known about how students with visual impairments access and interpret these types of visually-dependent instructional materials. This study explored the efficacy of new haptic (simulated tactile feedback and kinesthetics) instructional technology for teaching cell morphology and function to middle and high school students with visual impairments. The study examined students' prior experiences learning about the cell and cell functions in classroom instruction, as well as how haptic feedback technology impacted students' awareness of the 3-D nature of an animal cell, the morphology and function of cell organelles, and students' interest in the haptic technology as an instructional tool. Twenty-one students with visual impairment participated in the study. Students explored a tactile model of the cell with a haptic point probe that allowed them to feel the cell and its organelles. Results showed that students made significant gains in their ability to identify cell organelles and found the technology to be highly interesting as an instructional tool. The need for additional adaptive technology for students with visual impairments is discussed.

KEY WORDS: blind; haptics; tactile; technology; visually impaired.

INTRODUCTION

"When the other students do labs, I just sit there." This quote from a middle school student represents the reality of science education for many students with visual impairments. Traditional pedagogy is highly dependent on visual models of science phenomena, particularly as a student moves into secondary education. Instruction in chemistry, physics, microbiology, and earth and space science are filled with visually complex concepts that are difficult to access without vision. Imagine trying to understand the layers of the atmosphere, DNA transcription and translation, or geologic time without the aid of visual models and representations.

According to the American Federation for the Blind (2003) there are approximately 10 million blind and visually impaired people in the United States. Of these, approximately 93,600 are visually-impaired students who are served in school special education programs. Visual impairment is defined here as "an impairment in vision that, even with correction, adversely affects a child's educational performance" (See IDEA's Definition of Disabilities at: //www.ed.gov/databases/ERIC_Digests/ed429396.html). Students with visual impairments have the same range of cognitive abilities as other sighted students and with accommodations can master higher-order science concepts as well as students without visual impairments. However, traditional science instruction typically relies heavily on visual imagery and those

[1]Department of Mathematics, Science, and Technology Education, NC State University, Box 7801Raleigh, NC, 27695-7801, USA.
[2]College of New Jersey, Ewing, USA.
[3]Clemson University, Clemson, USA.
[4]To whom correspondence should be addressed; e-mail: Gail_Jones@ncsu.edu

with little or no vision have few avenues available to them to access science content and processes. A search of the literature for existing research on instructional materials, strategies, and interventions for teaching science to students with visual impairments revealed there is a severe dearth in this area of study.

Theoretical Background

The science classroom is saturated with representations of scientific concepts and it is through these representations that knowledge is communicated from teacher to students (van Sommeren *et al.*, 1998). Since students are commonly exposed to visual displays in textbooks, teacher presentations, and computer-based multimedia materials, the ability of students to interpret and understand these representations has become increasingly important in education (Ferk *et al.*, 2003). Because a majority of these representations are visual, students with visual impairments often experience academic problems.

For the regular education classroom science teacher, the challenges of teaching students with visual impairments are particularly difficult because with a few exceptions (e.g., Lang, 1983; Lunney, 1995; Lunney and Morrison, 1981; Malone and DeLucchi, 1979; Schleppenbach, 1996), there has been little effort to develop strategies and materials for these students. Stefanich and Norman (1996) report that the majority of science teachers and college science educators have little experience in teaching students with disabilities and teachers often hold stereotypical views of what these students are able to do. However, most educators in the Stefanich and Norman study believe students with visual impairment can become scientists such as chemists. Indeed, most students who have visual impairments have cognitive abilities equivalent to their peers but there seems to be a large gap between teachers' beliefs about students' capabilities and instructional resources available to help these students realize their full potential.

There is evidence that students with disabilities are often not given the same opportunities to experience science as non-disabled peers. Special education teachers often lack knowledge about the science curriculum, science content, and science pedagogy (McCarthy, 2005) and most often teach science out of the textbook (Patton *et al.*, unpublished). But recent research suggests that students need just the opposite to succeed in science. In a study that compared a textbook based approach and a hands-on science program it was found that students with disabilities did significantly better in the hands-on program (McCarthy, 2005).

Visualization in Science

Arguments have been made that scientists and engineers are characteristically visual thinkers and that scientific creativity is closely tied to visual imagination (Mathewson, 2005). Within the science community there are visual conventions that are shared understandings of images that have meaning across individual scientists (Arnold, 2001). Mathewson (2005) maintains that there are a number of images that cross science domains and are found at all levels of practice. These include images such as waves, webs, shadows, cycles, color, and coils. Very little is known about how people with visual impairments develop such concepts and the degree to which they are able to apply these to scientific phenomena in meaningful ways. Mathewson proposes that individuals learn science through increasingly complex visual learning that moves from perceptual to abstract levels. Mathewson's model begins with experiential (hands-on exploration), then moves to didactic, depictions, models, encoded, creative imagery, to end with intuitive discovery. According to this model the student moves up the ladder with increasing levels of abstraction and visualization. But what happens if a student lacks sight? Does Mathewson's model hold true for students who are visually impaired? Can a visually impaired student still achieve the highest levels of creative imagery or intuitive discovery?

While there is a growing research base examining the use of multimedia and computer-mediated instruction as a way to promote students' understandings of science concepts (e.g., Barnea and Dori, 1999; Barak and Dori, 2005; Dilek and Akaygun, 2004; Kozma and Russell, 1997; Mayer, 2003; Wu *et al.*, 2001), there is little research that directly investigates and documents how students with visual impairment learn science concepts and even fewer studies that explore the impact of technological tools designed for these students. In the present study we examine the efficacy of a unique haptic (involving touch and kinesthetics) tool as a mediator of information about cells for students with visual impairment.

The roots of the term ''haptics'' can be traced back the Greek word *haptesthai*, which translates to mean *able to lay hold of* (Krueger, 1989). With the advent of touch to computing the term today is often used when referring to the the study of touch and the human interaction with the external environment via touch. Recent developments in haptic technology have resulted in new types of force feedback joysticks. These new tools allow students to manipulate and get tactile feedback of three dimensional objects. Other researchers have investigated haptic technology as a tool for understanding docking positions for drugs (Brooks *et al.*, 1990), as well as for flight and medical training (Hayward *et al.*, 2004).

The haptic device used in the present study, the PHANToM®, utilizes a pen-like stylus that permits simulation of fingertip contact with virtual objects. As the student moves a virtual point-probe around in three-dimensional space, the PHANToM® tracks the *x, y*, and *z* Cartesian coordinates, as well as the pitch, roll, and yaw of the point-probe. Actuators communicate forces back to the user's fingertips as it detectes collisions with virtual objects, simulating the sense of touch (Salisbury *et al.*, 1995).

The development of new haptic tools such as the PHANToM® raises questions about how touch contributes to conceptual development and the perception of different materials. Mayer and his colleagues (1996) developed a cognitive theory of multimedia learning, which explains how people learn from visual and auditory stimuli. Specifically, Mayer's model proposes that learners engage in three active cognitive processes while viewing and listening to a multimedia presentation (Mayer and Anderson, 1991; Mayer and Moreno, 2003). These cognitive processes, which allow learners to construct a mental representation of presented material, involve selecting relevant words and images, organizing the relevant words and images to build verbal and visual models, and integrating them with one another and with relevant prior knowledge. Figure 1 illustrates the cognitive processes that take place while interpreting multimedia materials (Mayer, 2003, p. 129).

A central assumption of Mayer's model is that working memory has dual channels, a visual and a verbal channel. This idea is also a central feature of Paivio's dual-coding theory (1986) and Baddeley's theory of working memory (1999). However, what if students are not able to access the visual channel and develop a pictorial model? Is it possible for students to use another sensory modality? What happens when students (such as those with visual impairments) use haptic perception in place of visual imagery? The present study was designed investigate how students with visual impairment (thus replacing a significant part of Mayer's cognitive model with haptics) learn about cell morphology and function using a haptic computer-mediated instructional program.

METHODOLOGY

Research Goals and Questions

This exploratory study was designed to investigate how visually impaired students learn about cell morphology, as well as to examine how useful haptic technology may be for teaching science to students with visual impairments. Like many fields of study that are in their infancy, this study includes both descriptive and exploratory approaches. Within this broad framework, the specific research questions were:

a) How have students with visual impairments previously been taught about cell morphology and function?
b) Does haptic feedback impact students' with visual impairments:

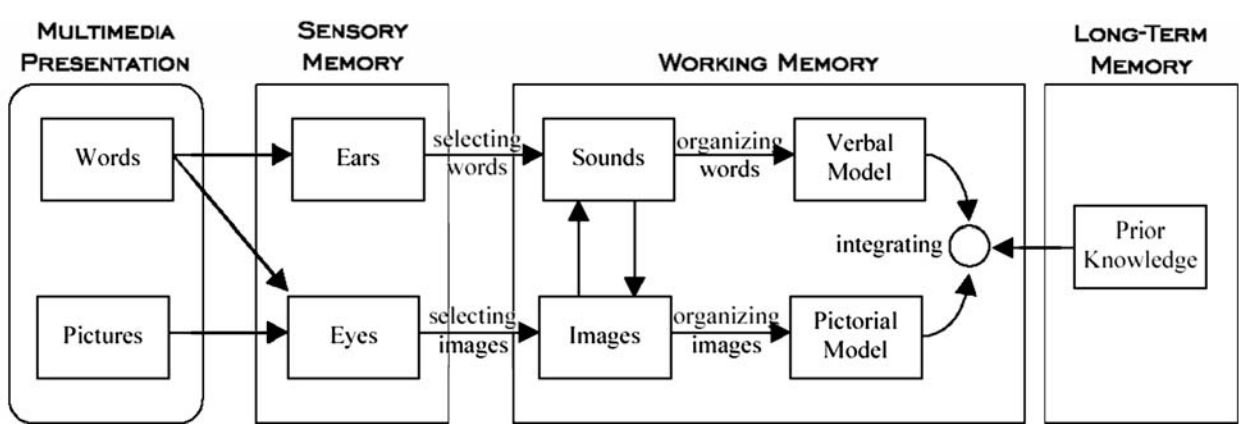

Fig. 1. A framework for the cognitive theory of multimedia learning proposed by Mayer.

- awareness of the 3-D nature of an animal cell?
- ability to recognize and name the organelles found in a typical animal cell?
- identification of the corresponding functions of an animal cell's organelles?

c) How interesting is the instructional program for students with visual impairments?

Instructional Program

Students in this study used the haptic feedback device known as the PHANToM® desktop device from Sensable Technologies. As described in the previous section, this innovative tool is connected to a desktop computer and ultimately allowed them to manipulate and get tactile feedback as they explored cell morphology depicted in the *Cell Exploration* program (Figure 2). This program began with a computer generated virtual model that depicted the 3-D nature and spatial arrangement of an animal cell with its characteristic organelles. The program allowed students to rotate and zoom in or out on the image of the cell being modeled visually and haptically. This unique bi-directional program and interface allowed students to ''feel'' the shape, size, texture, viscosity, and elasticity of the cell structures. Students could explore the cell membrane, cytoplasm, rough and smooth endoplasmic reticulum, Golgi body, vacuole, mitochondrion, lysosome, nucleus, and chromatin. As students moved the probe across the cell organelle the name of the organelle was announced.

Participants

Twenty-one students participated in the study (12 females, 9 males); all of the students were visually-impaired. Six of the students had no vision at all; other students' impairments varied from having some light perception (but unable to distinguish objects) ($n = 12$) to being able to read significantly enlarged text ($n = 3$). The mean age of participants was 15.5 years of age. All students had some prior experience learning about cells as part of their school science curriculum.

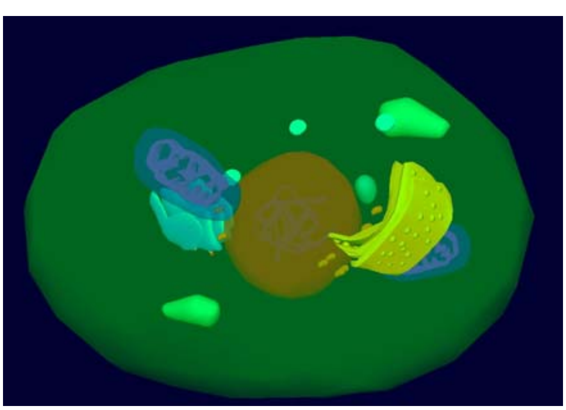

Fig. 2. A screenshot of the *Cell Exploration* instructional program.

Procedures

The participants rotated through a series of stations (described further below) and the activities at each station took approximately 15 min to complete (see Table I). A field researcher was present at each station to guide the students through the exercises and record data. First, students were pre-interviewed at the beginning of the study to determine their prior knowledge of cells, how they had been previously instructed about cells, and the degree to which the student was visually-impaired. This pre-assessment, framed within a qualitative and descriptive methodological approach, began by asking students to ''tell me everything you know about the cell.'' They were also asked to ''describe the structure of a typical cell, describe cell organelles, and to discuss how they had been previously taught about cells.'' Student responses were recorded by a field researcher.

Following the pre-assessment, students were trained in the use of the PHANToM® using a 3-dimensional modeling program. This program presented students with three basic geometric shapes (a sphere, cone, and cube) in succession and allowed the student to use the point probe to explore the geometry of the object using haptic feedback only. Participants were asked to verbally describe the object as they explored it. Checks were made to ensure that students were properly using the PHANToM®. Following exploration each student was asked to identify the object and was given feedback on his or her correctness.

After the training session, students used the instructional program (described earlier) to explore three virtual organelles (nucleus, Golgi body and

Table I. Instructional Stations

Station	Activity
Station 1	Pre-assessment
Station 2	PHANToM® training-3 shapes
Station 3	Cell program- explore individual organelles
Station 4	Post-assessment
Station 5	Cell program- identification of organelles within cell

endoplasmic reticulum). The virtual organelles were individually contained within a box and presented in isolation, one at a time. Students were asked to describe the organelle as they investigated its morphology with the haptic feedback device. Descriptions were recorded by a field researcher.

Upon completion of the organelle exploration each student was individually post-assessed. The assessment asked students to describe what they knew about the cell, describe the structure of the cell, and to describe the cell organelles. Students were also asked to rate how interesting the program was on a scale from 1 (not interesting) to 10 (highly interesting). Additional questions were asked to determine what other science topics students recommended for software development, as well as which science topics have been difficult to understand during science instruction. After the oral assessments, students were presented with foam organelle models (endoplasmic reticulum, nucleus, and Golgi body) for identification. Finally, students used the full *Cell Exploration Program* in which the whole cell was presented (with all of its typical organelles) and students were asked to locate the endoplasmic reticulum, nucleus, and Golgi body relying solely on the haptic feedback.

Analysis

The number of valid cell characteristics named in the pre- and post-interviews were determined. Two independent raters (experienced science teachers) rated each response for a total agreement across items of 97.5%. For example, a student noted, ‘‘the animal cell is round with the nucleus in the center; plant cells are rectangular.’’ This response was coded as having three correct cell characteristics: animal cells are round, plant cells are rectangular, and the nucleus is in the center.

Mean responses for how interesting was this experience were calculated. Descriptions of the organelles were coded by two researchers for haptic-related terms (texture, elasticity, geometry, bumpiness) and interrater agreement was determined to be 94%. Students' identification of foam models of organelles was coded as either correct (1) or incorrect (0).

RESULTS

Student Voices: Prior Instruction on Cells

During the pre-experience interview, students were asked to describe how they were taught about cells by their teachers. The student responses indicated that a variety of 3-dimensional models and tactile strategies were used including: the use of ‘‘puff paints’’ to depict cell parts, ‘‘edible models,’’ ‘‘raised drawings,’’ ‘‘tactile pictures,’’ ‘‘Braille worksheets,’’ and ‘‘graphic cells.’’ Auditory strategies used included ‘‘vocabulary,’’ ‘‘teacher explained it,’’ oral ‘‘vocabulary,’’ and a ‘‘book on tape.’’

For some students, teachers used visual strategies as the primary tool to teach students even though students lacked the vision to make use of these approaches. Students indicated that they were given textbooks, ‘‘a chart that was not in Braille,’’ ‘‘a microscope,’’ (that the student could not use) and ‘‘worksheets.’’ One student indicated that her teacher taught and she ‘‘just sat there’’ without any adaptations being made for her visual impairments.

Affect

All of the students who participated in the study reported that the instructional program was highly interesting with a mean rating of 8.65 on a scale of 1 (not interesting) to 10 (highly interesting). Observations of the students showed that students were highly engaged in exploring the organelles but had some difficulty discerning the morphology of each structure. Students expressed interest in having other applications developed that would allow them to explore other areas of science in addition to the cell.

Achievement

Students made significant gains from pre- to post-instruction on the number of valid cell parts they were able to recall. Before exploration students could name a mean of .91 cell parts. For example, when asked to describe the structure of a cell, Sam, (14 years of age) stated: ‘‘like a thing with a nucleus in the middle, between the nucleus and outside wall there is heredity material.’’ After instruction students were able to name a mean of 1.1 valid parts. Not only could they name more parts but they were able to give qualitatively more information about cells. For example, after experiencing the program Nicky (aged 15 years of age) stated, ‘‘the nucleus is in center; the ER is the rough part of the cell; the shape is round; plants (cells) are rectangular.’’

Students were also presented with 3-dimensional foam models and were asked to identify the cell organelle represented. The task required students to translate information they had perceived from the point-probe of the PHANToM® to a fully tactile 3-dimensional model. The nucleus was the most accurately identified organelle (88% of students), Golgi body was correctly identified by 33% of the students and the endoplasmic reticulum was identified correctly by only 19% of the participants.

Haptics

In their descriptions, students used more haptic words denoting texture, hardness, and geometry in their descriptions after using the haptic cell program. Before the instruction students used a mean of 0.1 haptic terms and after the program they used 2.5 haptic terms to describe cell organelles. An examination of the specific terms students used revealed that students were using the haptic clues as they conceptualized the organelles. For example, students' descriptions noted that "the Golgi body feels flat," "the endoplasmic reticulum had a crawl space in between, I felt like I was sliding along rubber bands," or the Golgi body is shaped like a skateboard."

Student Voices: Recommendations for Software

During post-experience interviews, students were asked if they thought the technology would be useful for learning about other areas of science. Topics students recommended for haptic software development included: feeling website pictures, volcanoes, cell division, contour and undersea maps, and hurricanes so they could feel the wall of the eye. Additionally, students suggested incorporating haptic feedback into instruction about gases and phase changes, stars and planets, atoms, proteins, microscope slides, anatomy, geometric figures, and musical notes.

Students were also asked what topics in science had been difficult for them as a visually-impaired person. A variety of topics were named including biology, earth science, how the body is made, shape of bones, diagrams, layers of the atmosphere, magnetism, invisible fields, volcanoes, electromagnetism, geologic time, equations, topographic maps, phases of cell division, chemistry, DNA, and microscopes.

DISCUSSION AND IMPLICATIONS

This exploratory study suggests that the haptic technology was effective in promoting initial learning about cell organelles for students with visual impairments. Students were able to identify and describe more cell parts following instruction with the haptic cell program. In addition, they were able to describe the organelles with significantly more haptic terms. One of the limitations of the technology for learning is that the PHANToM® is a point probe device and as such limited the geometric information that students were able to obtain during exploration of complex organelles. This constrained point-probe exploration requires the sequential tracking of the cellular components' contours and spatial patterns, a difficult task.

Perhaps more importantly, students reported that the haptic technology was engaging. The design of the program allowed the learner to control the pace and access of information, allowing the student to make sense of the instruction in ways that are not accessible when learning from a teacher's or peer's verbal instruction.

What is not clear is how the students in the present study were able to form concepts of cell organelles and the cell morphology. To what degree were they able to use haptic information in their conceptualizations? However, the students in the present study were legally blind and had very little or no visual perception and were therefore "blocked" in their access to the visual channel. How did the students process the sensory information to form concepts of cell morphology? Students' use of haptic terminology in their descriptions suggests that at least to some degree they were using the haptic properties of the organelles to conceptualize the organelle morphology.

Although Mayer didn't address haptics specifically, his work suggests that when the learning context utilizes haptic properties, students will clue into the haptic dimension of the learning task. If given both haptic and auditory media, how do the different sensory modalities contribute to a combined conceptualization? If learners process tactile information in a manner similar to verbal or visual information, perhaps they begin by selecting some of these tactile representations for further processing in working memory. Next, the selected tactile information would then need to be organized to yield a tactile mental model. However, the nature and structure of such a haptic mental model is not fully known. Finally, to yield an integrated representation of the presented material that can be stored into long-term memory for retention, one-to-one connections between the tactile model and the verbal model would need to be built. Again, a complete understanding of how this is accomplished by the learner has not yet been determined.

The students' interest in haptic technologies and their insightful recommendations for future applications suggests that they believe the PHANToM® has great potential as a learning tool. Students expressed their need for assistive technologies that can help them learn science concepts and phenomena. The majority of the students' teachers used visual and auditory strategies to help them learn. With a few notable exceptions, there were limited efforts made by teachers to provide tactile models for students. Clearly there is a strong need for a variety of strategies and models for teachers to use when teaching about the cell as well as other subjects. Students with visual impairments reported that those topics that are difficult to experience directly are difficult for them to learn, including topics at the microscale as well as those at the macroscale such as volcanoes or atmospheric science. Given the large number of students with visual impairments that attend public schools today and the small number of specialized pedagogical strategies, modified curricula, and assistive technologies, this is clearly an area of great need.

REFERENCES

American Federation for the Blind (2003). Blindness statistics. Retrieved on July 20, 2005 from: www.afb.org/Section.asp?SectionID = 15.

Arnold, K. (2001). Between explanation and inspiration: Images in science. In S. Ede (Ed.), *Strange and Charmed: Science and the Contemporary Visual Arts* London: Calouste Gulbenkian Foundation.

Baddeley, A. (1999). *Human Memory*, Allyn & Bacon, Boston, MA.

Barak, M., and Dori, Y. (2005). Enhancing undergraduate students' chemistry understanding through project-based learning in an IT environment. *Science Education* 89: 117–139.

Barnea, N., and Dori, Y. J. (1999). High-school chemistry students' performance and gender differences in a computerized molecular modeling learning environment. *Journal of Science Education and Technology* 8: 257–271.

Brooks, F. P., Ouh-Young, M., Batter, J. J., and Kilpatrick, P. J. (1990). Project GROPE-Haptic displays for scientific visualization. *ACM Computer Graphics* 24: 177–185.

Dilek, A., and Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching* 41: 317–337.

Ferk, V., Vrtacnik, M., Blejec, A., and Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education* 25(10): 1227–1245.

Hayward, V., Oliver, R. A., Cruz-Hernandez, M., Grant, D., and Robles-De-La-Torre, G. (2004). Haptic interfaces and devices. *Sensor Review* 24: 16–29.

Kozma, R. B., and Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching* 34: 949–968.

Krueger, E. L. (1989). *The World of Touch, by David Katz*., Lawrence Erlbaum, Hillsdale, NJ.

Lang, H. G. (1983). Preparing science teachers to deal with handicapped students. *Science Education* 67(4): 541–547.

Lunney, D., and Morrison, R. C. (1981). High technology laboratory aids for visually handicapped chemistry students. *Journal of Chemical Education* 58: 228–231.

Lunney D. (1995) Assistive technology in the science laboratory: A talking laboratory work station for visually impaired science students. Journal of Information Technology and Disabilities 2(1), http://www.rit.edu/~easi/itd/itdv02n1/lunney.htm.

Malone, L., and DeLucchi, L. (1979). Life science for visually impaired students. *Science and Children* 16(3): 29–31.

Mathewson, J. (2005). The visual core of science: Definition and applications to education. *International Journal of Science Education* 27: 529–548.

Mayer, R. E. (2003). The promise of multimedia learning: Using the same instructional design methods across different media. *Learning and Instruction* 13(2): 125–139.

Mayer, R. E., and Anderson, R. B. (1991). Animations need narrations: An experimental test of a dual-coding hypothesis. *Journal of Educational Psychology* 83(4): 484–490.

Mayer, R. E., Bove, W., Bryman, A., Mars, R., and Tapangco, L. (1996). When less is more: Meaningful learning from visual and verbal summaries of science textbook lessons. *Journal of Educational Psychology* 88(1): 64–73.

Mayer, R. E., and Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist* 38: 43–52.

McCarthy, C. (2005). Effects of thematic-based, hands-on science teaching versus a textbook approach for students with disabilies. *Journal of Research in Science Teaching* 42: 245–263.

Paivio, A. (1986). *Mental Representation, A Dual Coding Approach*, Oxford University Press, Oxford, England.

Salisbury, K., Brock, D., Massie T., Swarup, N., and Zilles, C. (1995). Haptic rendering: Programming touch interaction with virtual objects. Proc. *Symposium on Interactive 3D Graphics*, ACM. pp. 123–130.

Schleppenbach D. (1996) Teaching science to the visually impaired: Purdue University's Visions Lab. Journal of Information Technology and Disabilities 3(4), http://www.rit.edu/~easi/itd/itdv03n4/article1.htm.

Sensable Technologies, Phantom Desktop Haptic Device, http://www.sensable.com/products/phantom_ghost/phantom-desktop.asp.

Stefanich, G. P., and Norman, K. I. (1996). *Teaching Science to Students With Disabilities: Experiences and Perceptions of Classroom Teachers and Science Educators*. A special publication of the Association for the Education of Teachers in Science.

van Sommeren, M., Reimann, P., Boshuizen, H., and Jong, T. D. (Eds.). (1998). *Learning with Multiple Representations*. Amsterdam, Permagon.

Wu, H., Krajcik, J. S., and Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching* 38: 821–842.